REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE** Technical Paper	**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE		**5a. CONTRACT NUMBER** F04611-95-C-0123
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		**5d. PROJECT NUMBER** 1011
		5e. TASK NUMBER 00KQ
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Pratt & Whitney		**8. PERFORMING ORGANIZATION REPORT**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048		**10. SPONSOR/MONITOR'S ACRONYM(S)**
		11. SPONSOR/MONITOR'S NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Leilani Richardson
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	A		**19b. TELEPHONE NUMBER** *(include area code)* (661) 275-5015

122044

3 separate items are enclosed

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FROM: PROI (TI) (STINFO) 08 Jun 2000

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Jennings, T., Fentress, S., Lyda, R. (Pratt & Whitney), "Fabrication and Test of an Advanced Expander Combustor"

AIAA Joint Propulsion Conference **(Statement A)**
(Huntsville, AL, 17-19 Jul 00) **(Submission Deadline: none given)**

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AIAA

? PLANNED TESTING

AIAA 2000-3776
FABRICATION AND TEST OF AN ADVANCED EXPANDER COMBUSTOR

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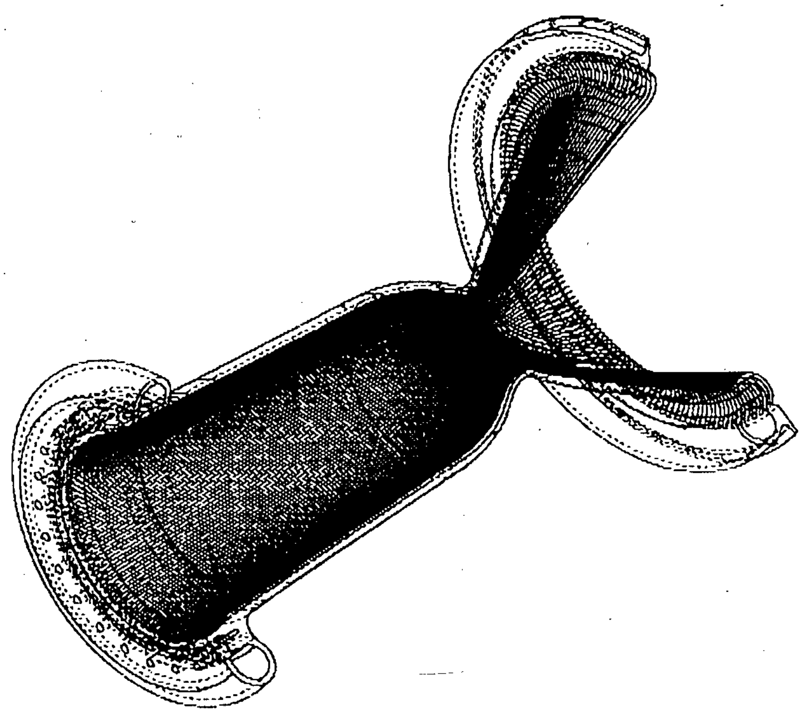

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36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit
July 17-19, 2000 / Huntsville, AL

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ABSTRACT

This paper discusses fabrication and test of an advanced expander combustion chamber for a 50,000 pound (222.4 KN) thrust Upper Stage Expander Cycle Engine. The chamber is being developed by Pratt & Whitney Liquid Space Propulsion under contract for the United States Air Force Research Laboratory (AFRL) to support the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) initiative ~~program.~~ The Advanced Expander Combustor is designed to provide increased heat pick-up to the coolant and improved system thrust to weight, increased specific impulse, and increased reliability.

INTRODUCTION

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The Air Force, Army, Navy, and NASA have implemented a three-phase, 15-year rocket propulsion technology improvement effort to "double rocket propulsion technology by the year 2010". This initiative, designated the Integrated High Payoff Rocket Propulsion Technology (IHPRPT), establishes performance, reliability, and cost improvement goals for each of the three phases. These goals are to be met by advancing component technology levels through design, development, and demonstration, followed by an integrated system level demonstrator to validate performance to the IHPRPT system level goals. Pratt & Whitney Liquid Space (P&W) Propulsion, under contract to the United States Air Force Research Laboratory (contract F04611-95-C-0123), is developing the Advanced Expander Combustor (AEC) combustion chamber. This combustion chamber is designed to be used with the 50k LOX/Hydrogen Upper Stage Demonstrator (Ref. AIAA 2000-3874 *Development Status of a 50k LOX/Hydrogen Upper Stage Demonstrator).* This demonstrator will be test fired to demonstrate the IHPRPT LOX/LH2 boost/orbit transfer propulsion area Phase I goals. These system level goals include; a 1% improvement in vacuum specific impulse, a 30% improvement in thrust to weight, a 15% reduction in hardware/support costs, and a 25% improvement in reliability relative to the current state-of-the-art engine baseline.

The component goals, established for the AEC to support the resulting cycle and IHPRPT goals, are as follows:

1) Increase coolant heat pick-up by 300% with respect to the current state of the art baseline.
2) Maintain coolant pressure drop to within 50 psia (3.5 kg/cm**2) with respect to the current state of the art baseline. ?
3) Maintain combustion chamber fabrication costs of the current state of the art baseline.

The AEC design accomplishes these goals. The heat pick-up is increased 300% while simultaneously reducing the required heat exchanger area to approximately 37% of the baseline. Similarly, the heat transfer to normalized pressure drop is increased by a factor of 2.1. Achievement of the above AEC component goals results in a 10% improvement in engine thrust-to-weight and 1% improvement in specific impulse relative to the baseline.

DISCUSSION

The simplicity of the expander-cycle engine offers the ability of placing payloads into orbit at lower cost. Current expander cycle engines are limited in their ability to increase chamber pressure, due to the low heat transfer afforded by the materials used in the combustion chamber. Development of an advanced-technology combustion chamber that increases chamber pressure and provides more performance while maintaining reliability and operability are the primary goals.

An expander-cycle rocket engine cools the chamber/nozzle components with the engine fuel flow. The turbopumps are powered with the energy picked up by the cooling process. The turbine inlet temperature created by this cycle results in weight, cost, and reliability advantages over other cycles (i.e., gas generator, staged combustion). Expander-cycle engines have lower turbopump pressure requirements than staged combustion engines and higher performance potential than gas generator cycles. In order to attain the highest thrust in the smallest dimensional envelope, the combustion chamber heat pickup must be maximized.

start

P&W created an advanced expander engine model, which meets the IHPRPT Phase I system level goals, from which component goals could be determined. The P&W RL10 was used as the starting point for developing the advanced expander engine cycle. The RL10 utilizes a two-stage turbine driven by the expanded hydrogen from the combustor and nozzle cooling tubes. The turbine drives both the two-stage hydrogen turbopump and, through a gearbox, the single stage Liquid Oxygen (LOX) turbopump. The expander cycle, developed for the RL10, is shown in Figure 1. The advanced expander engine cycle will allow further growth of 30,000 Lbf (133.4 KN) to 40,000 Lbf (177.9 KN) of thrust.

The growth potential of the current RL10 family is limited by the fuel pump discharge pressure which is in turn limited by the heat pickup capacity of the combustor and nozzle cooling tubes. While a tubular construction provides higher heat transfer surface area than a flat walled milled channel combustor, the moderate conductivity of the RL10 tubes limit the heat load capacity per unit area. The ability to transfer more heat across the chamber cooling wall is essential to providing the increased energy required for higher turbopump output, chamber pressure, and thrust, in the advanced expander cycle.

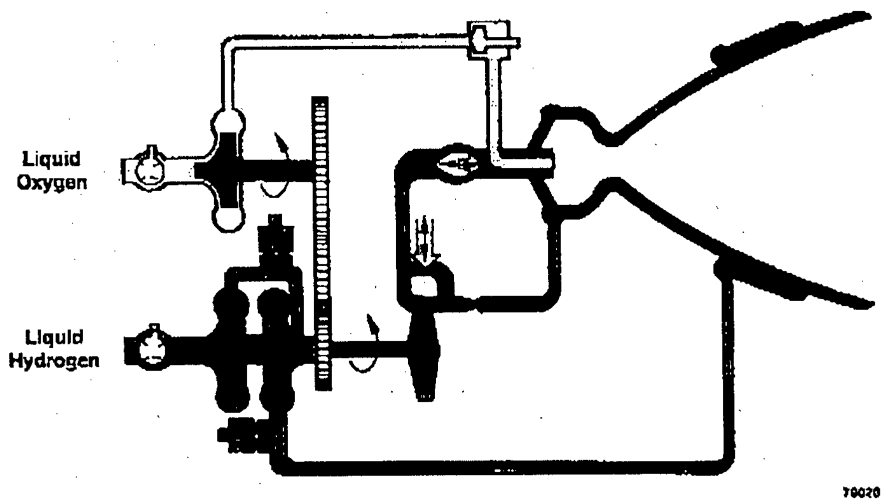

Figure 1 - RL10 Expander Cycle System ~~with Gearbox~~

Until recently no significant improvement in thermal conductivity was available without an unacceptable sacrifice in material properties such as strength, Low Cycle Fatigue (LCF) characteristics, and oxidation/erosion capability. This problem has been solved by the development of PWA 1177 which provides improved material strength, LCF capability, and conductivity. The Advanced Expander Combustor ~~(AEC) being developed for the AFRL on contract F04611-95-C-0123~~ uses PWA 1177 to provide the increased heat transfer and resultant energy required to support the advanced expander engine cycle.

The additional heat load capacity provides the required turbine input energy necessary to support an increase in the turbopump discharge pressures, allowing an increase in chamber pressure. Analysis of an expander cycle with the improved heat load capacity supports a stable expander cycle operating at a chamber pressure and fuel pump discharge pressure greater than the baseline. The final system balance provides a heat load capacity sufficient to drive both the fuel turbopump and the oxidizer turbopump with margin to spare.

THE ADVANCED EXPANDER COMBUSTOR DESIGN

The AEC design goal is to maximize coolant heat pick-up with a minimum coolant pressure drop, chamber weight and production cost. The accommodation of high heat flux levels requires thermally compliant chamber materials and geometries with high strength liners. The enabling design feature of the AEC is the use of a high strength, high conductivity material, Pratt & Whitney PWA 1177, in a tubular combustor configuration.

The AEC, which is shown in Figure 2, has been designed to provide:

- A naturally compliant pressure vessel shape for reduced strain levels in response to thermal stresses.
- Reduced pressure losses of the hydrogen coolant.
- Tubular geometry allowing the maximum surface area and heat pick-up.

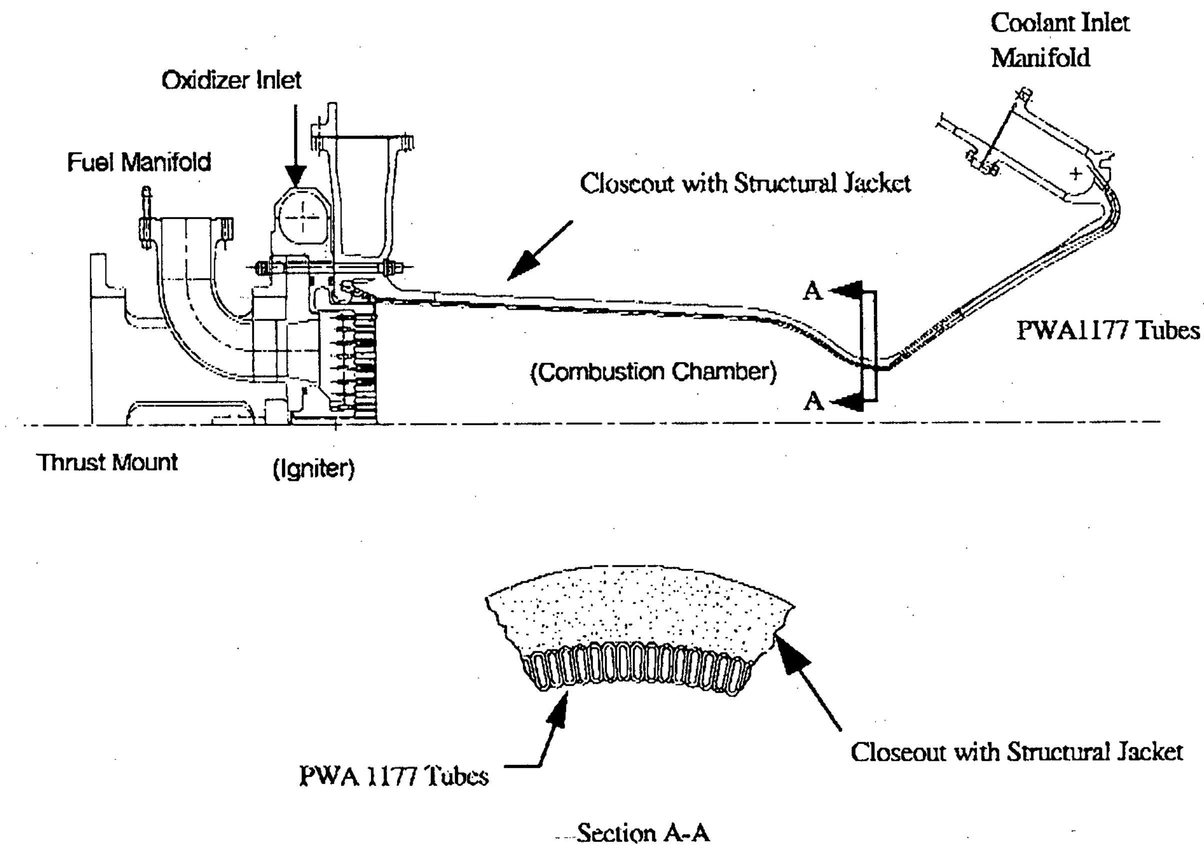

Figure 2 - Cross Section of the Advanced Expander Combustor

TUBULAR LINER DESIGN

The challenges of the AEC liner design are to maximize coolant heat pick-up, minimize coolant pressure drop, increase strain range tolerance and ductility, maintain liner material properties throughout the fabrication process, and increase the liner creep strength.

Following a thorough examination of various options in chamber construction, P&W selected a tubular thrust chamber. ~~The most~~ significant feature is the use of a new alloy (PWA 1176) coupled ~~with an~~ improved processing technique (PWA 1177). Using P&W's Rapid Solidification Rate ~~(RSR)~~ technology, a new, optimized alloy was created that enables the fabrication of high-strength, temperature-resistant

?

The three primary requirements for a successful braze process are braze temperature control, proper joint fit, and proper braze alloy placement. A low temperature braze alloy was utilized for joining and sealing the PWA 1177 tubes to the manifolds. Torch brazing and soldering are ideal techniques for joining gaps 5 to 10 mils or larger. Using a filler with a wide melting range enables loose fitting joints to be torch soldered or brazed with relative ease. The simplicity of the equipment required also allowed development work to proceed much more rapidly than it could if a vacuum furnace or hydrogen retort were employed.

STRUCTURAL JACKET DESIGN

The AEC structural jacket design is to provide thermal compatibility with the chamber liner, accommodation of hoop and axial loads, and a low risk manufacturing approach for demonstrating the tubular technology. The structural jacket is applied using a plating process. Dimensional tolerances are significantly relaxed since precise fit controls are not necessary. This approach is a proven viable method for producing thrust chambers. For the AEC, closeout of the PW1177 tubes is accomplished using a fine-grained plating process applied to a minimum thickness above the tube crowns. This provides excellent mechanical performance and physical characteristics. The bond strength of the closeout to the primary substrate becomes highly dependent on the strength of the interface. Application of a structural jacket follows the closeout.

Provisions for tube wall instrumentation are made during the plating process . Over 25 temperature measurements of the tube walls at various circumferential and axial locations are planned during hot fire testing of the chamber. Thermocouples will be epoxied to the final jacket assembly and monitored during cooldown and hot fire testing.

INJECTOR DESIGN

P&W has designed and fabricated an injector which is planned for use during testing of the AEC. This injector was designed for high combustion efficiency with minimal circumferential wall heat flux and mixture ratio variations. Concentric elements were selected to provide a high degree of gaseous fuel and liquid oxidizer atomization, vaporization, and mixing. A torch igniter was selected for the AEC since all tests planned are single ignition events. The torch was chosen because of previous experience with this type of ignition device in this type of test program where a high energy source is required. In this type of test environment, the igniter can be started and verified prior to introducing propellants to the combustion chamber, thus ensuring robust, reliable single ignition events.

Aerothermal Design Laboratory waterflow testing shows that the injector for the Advanced Expander Combustor has a fairly even distribution of mixture ratio across the injector.

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AEC E8 TEST FACILITY

A schematic of the E-8 test facility is shown below as Figure 4.

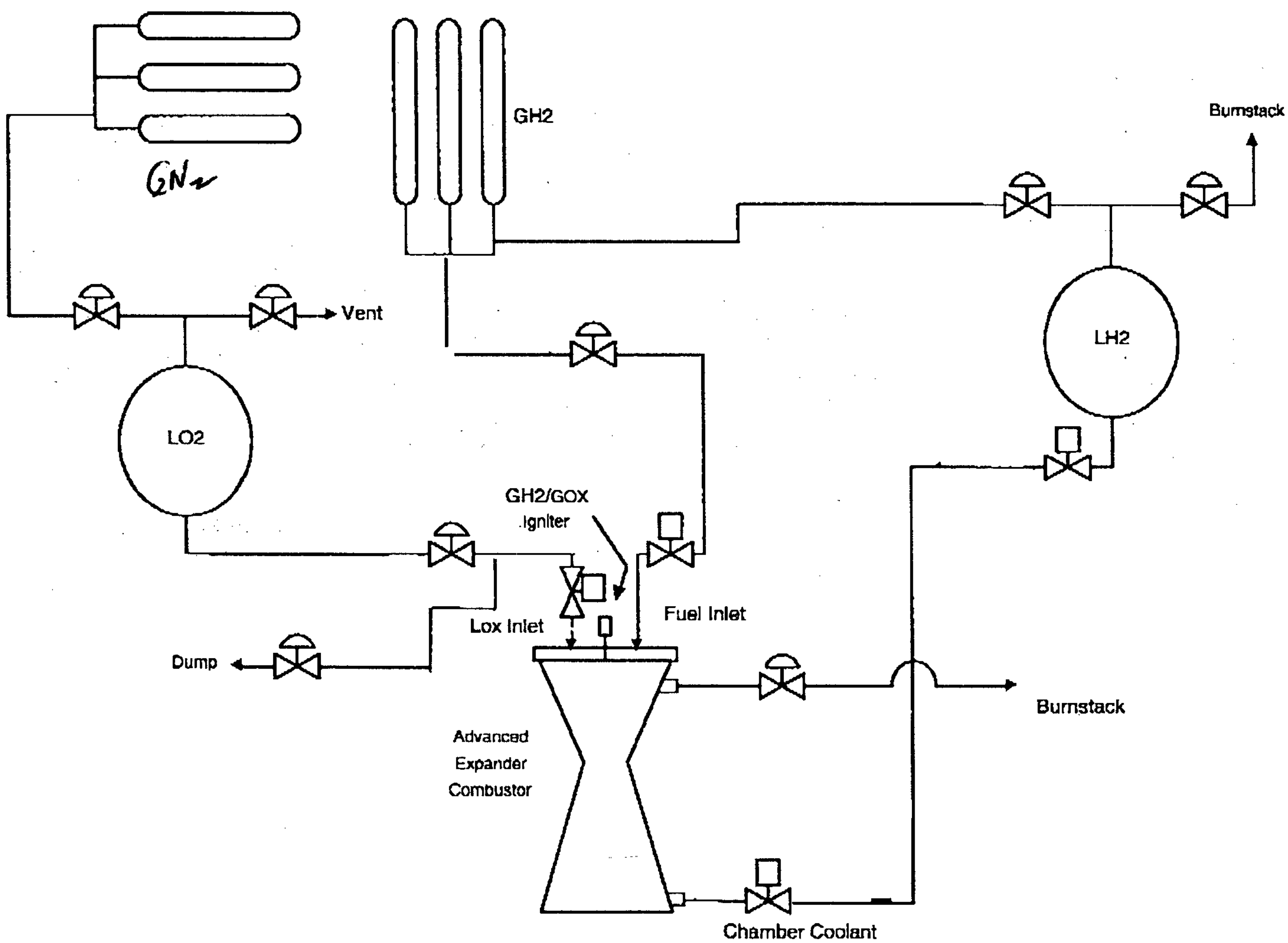

Figure 4 - AEC E8 Test Facility

In general, the facility is made up of three distinct sections. The high pressure liquid oxygen leg provides oxidizer to the test rig from a large capacity tank. Control valves are used for scheduling of LOX to the test article. The high pressure GH2 leg provides fuel to the test article from six GH2 high pressure storage vessels. Control valves are used for scheduling of GH2 to the test article. The AEC coolant leg provides liquid hydrogen to the test article from a large capacity tank. Control valves are also used for scheduling of coolant flow to the test article.

AEC AND FACILITY MODEL OVERVIEW

set

A transient math model for the AEC and test facility has been created with the P&W/NASA MSFC ROCket Engine Transient Simulation (ROCETS) system. ROCETS consists of a library of module building codes, a processor to configure the modules into a user defined system simulation and a processor to execute the simulation as defined by the user. The math model represents the AEC and facility through high fidelity physics, fluid dynamics, thermodynamics, and heat transfer. Combustion properties are obtained from the NASA ODE database and real fluid properties from the NIST database.

The model incorporates:

- volume dynamics,
- facility plumbing line losses,
- multi-volume AEC heat transfer characteristics,
- injector characteristics based on actual water flow testing,
- valve characteristics and actuator dynamics,
- controller characteristics,
- active injector purges,
- injector routine which accommodates both single phase and two phase operation.

The model was used in a teaming environment with the projects group, aerothermal group, and test operations group to establish facility and test requirements. Specifically, these requirements include:

- start, power level ramps, shutdown and steady state sequencing procedures,
- test planning support,
- pre-run predictions,
- plumbing design support,
- valve requirements and scheduling,
- purge flow requirements,
- closed loop control requirements and methodology if needed.

The final requirements for testing of the AEC will be defined following cold flow testing of the valves and start/ignition testing using an expendable chamber.

AEC VALIDATION TESTING

Support personnel from Pratt & Whitney along with members from United States Air Force Research Laboratory have laid out a test plan for the AEC to gather the necessary performance information within the required budget constraints. The test program consists of seven tests. These tests include:

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- Three tests to determine the test facility flo characteristics (LO2, GH2, LH2),
- One test to establish torch igniter functionality and procedures,
- One hot fire test of the AFRL supplied expendable chamber to validate the injector and facility start transient,
- Two hot fire tests of the P&W chamber to demonstrate operability at the 60% and 100% power levels.

Q, ? MEANS

Cold flow testing will be initially conducted with LN2 to verify the valve and plumbing characteristics associated with the high pressure LOX system. Following these tests, initial combustion system verification testing will be conducted on an expendable chamber provided by the Air Force Research Laboratory. Early in the test planning phase of the program, AFRL and Pratt and Whitney developed a mitigation strategy to reduce the risk associated with hot firing the AEC at the new test facility using an injector with no hot fire time accumulated. To mitigate this risk, AFRL and P&W decided to use an expendable chamber to test fire the injector and facility before mounting the AEC. The new chamber was designed to have the same interior profile as the AEC chamber. A jacket was also provided by AFRL to structurally contain the expendable liner, provide the injector mount and provide a positive seal for the combustion chamber.

Tests scheduled with the expendable chamber include:

- GH2 facility flow characteristics,
- injector priming characteristics,
- ignition characteristics,
- steady state and transient injector performance.

Information obtained from the cold flow testing and testing with the expendable chamber will be incorporated into the AEC model. Final requirements and procedures will then be determined based on updated model results. Testing of the AEC will consist of hot firings to validate the combustion efficiency and stability as well as the AEC regenerative heat load. Thermocouples attached to the backside of the chamber will be used to map the AEC heat flux profiles.

All phases of testing are anticipated to provide a great deal of quality information especially when conducted with the test operations, instrumentation, and data system support groups that have been tried and proven from other programs such as the RL10, ALH (Advanced Liquid Hydrogen), and ATD (Alternate Turbopump Development).

Information gathered through these tests will be used to update models ~~for future design~~ AFRL considerations of the Upper Stage Development (USD) engine system.

SUMMARY AND CONCLUSION

Pratt & Whitney's Advanced Expander Combustor integrates state-of-the-art material, a high performance thrust chamber geometric configuration, and advanced fabrication approaches into a thrust chamber unit that supports the IHPRPT Phase I goal.

The AEC is expected to test at Pratt & Whitney's Florida test facilities by mid 2000. The AEC test requirements have been integrated with the Air Force Research Laboratory in parallel with fabrication to ensure the facility is ready to support testing of the AEC.